Advanced Single Degree of Freedom Shaker Qualification:
A White Paper on the Near-Term Benefit of Proposed Technical Research
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1) Introduction to Vibration Qualification Testing Shortcomings and Proposed Research Solutions

A community of practice of 30 different organizations was assembled to address long standing vibration qualification testing deficiencies negatively impacting cost, schedule, and reliability. A survey of 10 of those organizations identified three technology research topics[1] with near term benefit potential for reducing cost and schedule and increasing quantifiable reliability. This paper addresses one of those three topics, to establish improved Single Degree of Freedom (SDOF) vibration shaker qualification testing. For brevity hereinafter, a vibration shaker qualification test will be referred to as a "test." The payload or component subject to such a test will be referred to as the "component." The acceleration response of the component when it is mounted in the system experiencing the expected vibrations in the field is referred to as the "field service environment" or FSE.

1.1) One challenge is that current standard SDOF vibration qualification testing cannot quantify the margin of the laboratory SDOF test with respect to the component FSE damage potential. No current damage potential metrics are utilized to relate the SDOF test to the FSE damage potential.

1.2) SDOF test specifications are written in terms of a base input acceleration that comes (ideally) from a base input acceleration measured in the FSE. However, the specification is not adjusted for the difference in the FSE and SDOF test boundary conditions which drastically change the laboratory response dynamics from the FSE response. Ignoring the differences in boundary conditions generally causes a severe over-test at the laboratory resonant frequencies. In some cases, the SDOF over-testing leads directly to costly and time-consuming component redesign, requalification, and an increase in weight.

1.3) A "perfect" SDOF test base input is ideally in one direction. However, all SDOF shaker facilities involve the shaker, slip table, expander head, and fixtures that contribute to resonant dynamics that will be active during the test. Unavoidably, some of these dynamics will provide input motions in other directions besides the desired one, as well as pitch, roll, and yaw input. These unavoidable inputs are usually ignored, but they can drive component damage potential response that is NOT in the FSE.

1.4) The required solution would transform the component damage potential of the FSE response to the best SDOF test with known uncertainty. This allows decision makers to

determine what is the best suite and amplitude of SDOF (and, if necessary, Multi-DOF or field) tests to reduce the risk of component failure in the FSE and quantify the margin associated with the qualified component. A qualified component would result with a quantified margin to ensure confidence (as opposed to the current unquantified approach). This solution would also mitigate SDOF over-testing that can cause unnecessary costly and lengthy component redesigns or even shaker damage.

2) Problem Statement: A traditional SDOF test has unknown margin with respect to the field service environment damage potential

To illuminate the traditional SDOF test problems, consider the simplest case of a base mounted component. The component is instrumented with several accelerometers to measure the field vibration response, known as the FSE. The component is mounted on a plate inside the full system, which is subjected to a vibration environment. The simplest base input that the system imparts upon the component can be described with six motions at the component base in the x, y, z, pitch, roll, and yaw directions. These base inputs move the component in proportional rigid body vibrations and excite elastic modes at resonant frequencies in the system. In the rigid body vibrations, the component rides with the base motions without strain, but the elastic modes will cause vibrating strain in the component. The laboratory qualification is typically performed with three non-simultaneous SDOF tests, one with base input in the x direction, one with input in the y direction, and one with input in the z direction. Consider just the x direction SDOF test. The design of the shaker is to attempt to completely constrain y, z, pitch, roll, and yaw and provide ONLY x input. This changes the resonant frequencies of the SDOF test from those in the field. However, the resonant changes are completely ignored, and an x direction field acceleration measured somewhere around the base of the component is utilized as the input, usually with some conservative envelope. A case study is provided to show a typical result. Figure 1 shows a simple base mounted component which had four triaxial accelerometers on it, each able to measure an x, y, and z direction response.

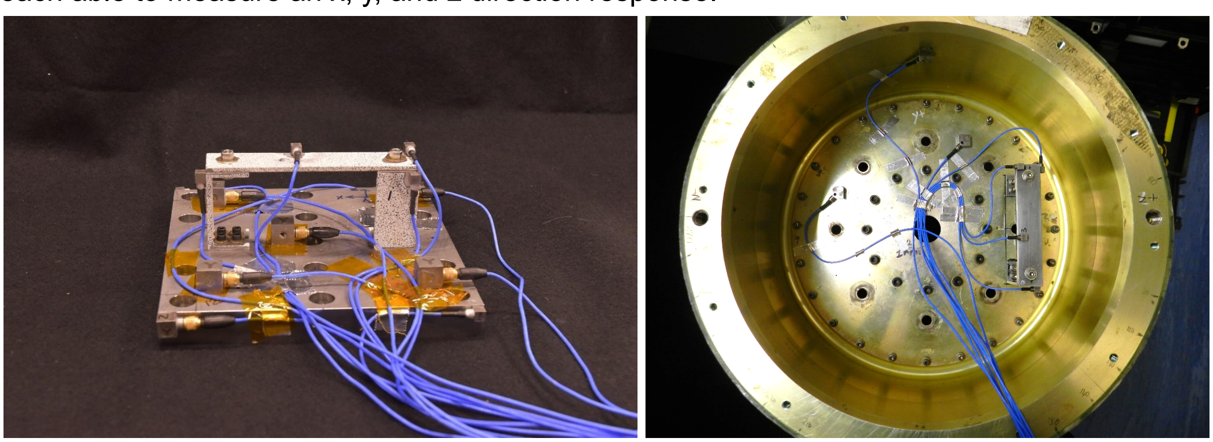

Figure 1 - A Simple Base Mounted Component with 4 Triaxial Accelerometers to Measure Lab (Left) and FSE (Right) Response

The component was mounted on a plate inside a system subjected to random vibration and the field measurements were processed in the frequency domain. The component response model to all six base inputs was extracted from a laboratory 6DOF shaker random survey. Then only the measured x field input was applied to the component response model, (i.e., y, z, pitch, roll, and yaw inputs were set to zero) yielding a guaranteed SDOF input. Figure 2 shows the field acceleration auto spectral density (ASD) of accelerometer 1X and compares it with the SDOF simulated response from a perfectly controlled base x input.

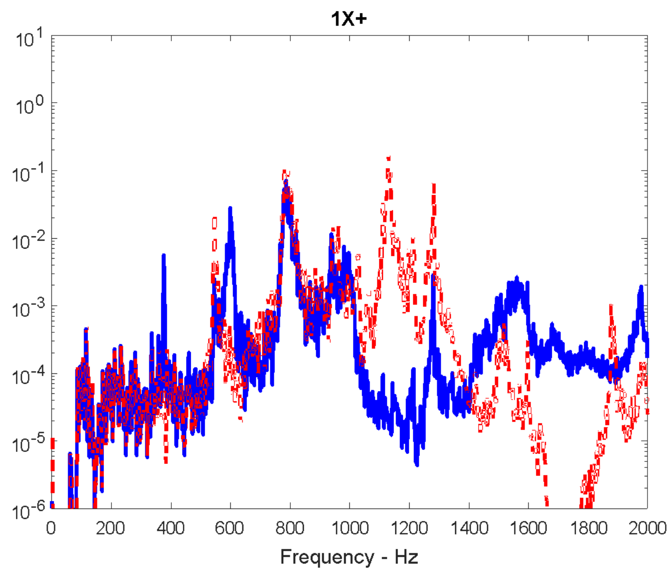

Figure 2 - Component ASD at 1X Comparison: FSE (blue) and SDOF Test Simulation with Measured Field Base Input in only x Direction

The desired response is for the red ASD to match the blue FSE response. However, the differences in the laboratory and field boundary conditions were not considered. Up to 1000 Hz in the x direction is not too bad since the component is just riding along in rigid body motion. Of notable concern, near 1100 Hz the magnitude of the SDOF ASD is ***four orders of magnitude*** greater than the FSE response. This is known to be the component's first laboratory resonant frequency in the x direction. In stark contrast, near 1700 Hz the magnitude of the SDOF ASD is four orders of magnitude deficient. Given the exceedance and the deficiency, what is the structural margin for this case study? Does the exceedance mean that the component is going to break in the lab test when it would survive in the field? Does the deficiency mean that the component might fail in the field even if it survives the lab test? Generating the SDOF shaker vibration qualification test specification using more conservative straight-line enveloping of the component's FSE base input further increases the chance of unnecessarily breaking the component in the SDOF test. One cannot tell from this ASD whether the damage potential is appropriate. In the typical SDOF test no one would even look at this concerning comparison. Usually, the only comparison is the SDOF base input acceleration with the base input specification.

2.1) This simple case study shows that we do not know if the typical SDOF test damage potential is more or less than the field damage potential. The typical ASD plot, which is usually only given for the base input instead of the response, may actually mask more appropriate damage metrics.

2.2) The case study shows that we should account for boundary condition differences between the field and the lab in developing the base input specification.

2.3) This SDOF test simulation provided ONLY an x direction base input, but typical shaker facilities have unavoidable resonant responses that may drive some y, z, pitch, roll, or yaw unintentionally at some frequencies, with a possible unwanted and unquantified increase in damage potential.

3) Solution: Provide a technical basis to quantify the margin and/or uncertainty of the damage potential in SDOF tests with respect to the FSE

3.1) Comparing ***damage potential metrics*** derived from measurements in the FSE to the damage potential metrics derived from the suite of laboratory SDOF tests provides quantified margins and confidence. The additional benefit would be that SDOF tests would not unnecessarily break components due to unschooled over-tests resulting in time-consuming and costly redesigns and requalification. The margin and uncertainty quantification of SDOF test damage potential would also identify the cases when SDOF tests may be inadequate and additional Multi-DOF or field testing is required for qualification.
3.2) ***Transformation between the field and laboratory boundary conditions*** must be utilized to derive SDOF test base inputs. Multiple works have developed various methods that can be applied to transform from the field to laboratory boundary conditions[2-16]. Consider the experimental response model mentioned in Section 2 that was derived using Napolitano's method[9]. Using that response model to continue our case study but controlling all six DOF base inputs to achieve best fit to the 12 measured component FSE responses provides the ASD comparison given in Figure 3.

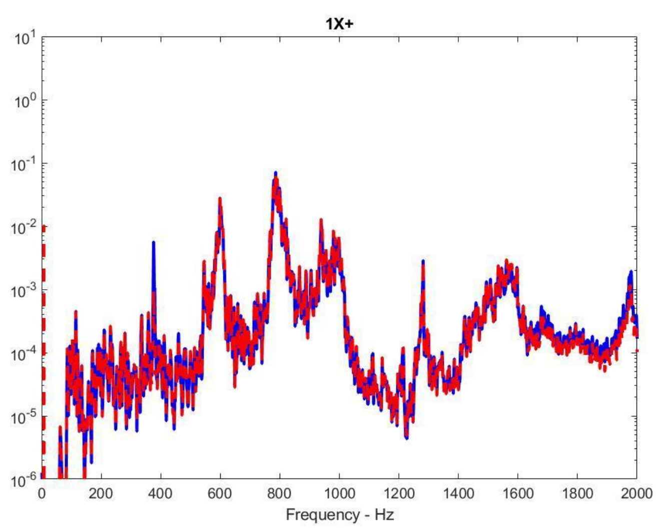

Figure 3 - Component ASD at 1X Comparison: Field (blue) and Controlled Six DOF Base Input (red)

Figure 3 shows that the experimental model accounting for boundary conditions can be used to derive accurate x, y, z, pitch, roll, and yaw base inputs on a 6DOF shaker that will closely reproduce the field measurements. Realizing that 6DOF shakers will not be available to most testing organizations in the near term, the same principles can be applied to derive an optimized SDOF x only base input that will provide a least squares match to the 12 FSE accelerations as

shown in Figure 4. For this simulation, the base input y, z, pitch, roll, and yaw accelerations were constrained to zero.

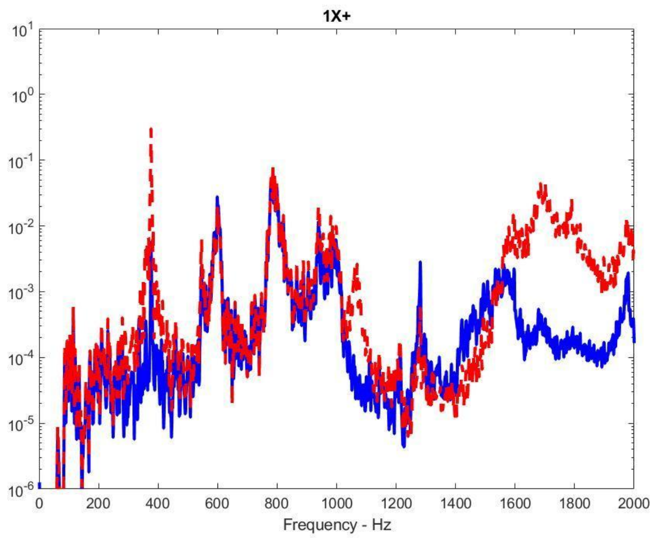

Figure 4 - Component ASD at 1X Comparison: FSE (blue) and SDOF Test Simulation ASD with Optimized x Direction Only Base Input (red)

The tailored lab x only input must be ***different*** from the field base x input associated with Figure 2 to account for the change from the field to the laboratory SDOF boundary conditions. In Figure 4 much of the ignored uncertainty apparent in Figure 2 is removed providing a much improved ASD response comparison. Extending the response information to optimize the input for damage potential metrics and adding appropriate conservatism where needed would provide quantified margin and confidence and be tailored to remove severe over-testing.
3.3) Providing ***full laboratory test planning models*** is a final step in near-term research. The SDOF model in Section 3.2 provides the response to a "perfect" SDOF x base input. However, SDOF facility shakers, slip tables, expander heads, and test fixtures have resonant dynamics in the typical testing bandwidth of 20-2000 Hz. These dynamics will cause the SDOF x direction shaker setup to impart some unavoidable y, z, pitch, roll, and yaw base input into the component response model utilized in Section 3.2. Therefore, a model of the facility shaker needs to be coupled to the component response model. This coupled model of the full laboratory test provides valuable planning information. Using the FSE component responses with the full laboratory model allows the calculation of the shaker input voltage in advance of the SDOF test. This allows a check to make sure the shaker facility electrical and mechanical limitations are not violated thus protecting the facility from costly damage and down time. In addition, the complete laboratory model will estimate the component damage potential response due to the undesirable but inevitable y, z, pitch, roll, and yaw inputs that will be driven by the shaker facility dynamics. Such information can be utilized to tailor the input so that unwanted shaker dynamics are notched to minimize laboratory damage potential that would NOT be characteristic of the FSE. In short, a well understood test plan could be developed that would produce the right suite of SDOF tests the first time. This planning tool mitigates costly and time-consuming facility damage or component breakage due to over-testing. Several works

have begun to develop the capability of coupling component response and shaker facility models[17-25].

4) Summary of Problem and Near-Term Research Solution

Near-term research solutions will drive significant savings in cost and time and increased qualification confidence for SDOF test methods. Current SDOF shaker vibration qualification test methods do not provide a quantified margin with respect to the component's field service environment damage potential. The laboratory boundary conditions cause resonant response at different frequencies and much higher amplitudes than the field response. If an unschooled over-test fails the component, an expensive and time-consuming redesign (and increase in weight) results. The more disastrous possibility of a laboratory under-test due to the uncertainty of the boundary condition with an associated field failure may have much more significant consequences of exorbitant expense. For example, a component failure in commercial planes has overwhelming down-time costs, penalty payments and threatens passenger safety. Six DOF laboratory testing has demonstrated that full compensation for the difference in field and laboratory boundary conditions is possible on a base mounted component. At least partial compensation has been demonstrated in SDOF tests. In the near-term, research should be undertaken in the areas of damage potential metrics, component response models, and test planning models to mitigate current SDOF testing deficiencies.

4.1) Damage potential metrics should be developed which relate the field failure modes to the laboratory. The metrics must be derived from response measures that can be obtained in the field and laboratory. Quantifiable margin would then be defined by the ratio of the laboratory metric divided by the field metric. Different metrics might address structural failure, fatigue failure, or functional failure. One example of a possible structural metric is modal potential energy which can be calculated from component acceleration responses and laboratory mode shapes.

4.2) Methods to efficiently generate experimental or analytical frequency response models for test components should be developed. Such a model allows calculation of the appropriate base input acceleration to best fit a desired set of component responses, accounting for the difference in laboratory and field boundary conditions. Then a suite of x, y, and z direction SDOF test specifications can establish appropriate conservatism but eliminate unnecessary over-testing. An example of such a model is the frequency response of component accelerations to the 6DOF shaker table head accelerations which can be derived from a low-level random survey with uncorrelated actuator input voltages.

4.3) Methods to efficiently generate full laboratory system test planning models should be developed to ensure that an appropriate suite of SDOF tests can be accomplished that will quantify margin, mitigate component over-testing, and stay within hardware limitations for a particular laboratory shaker. This requires the coupling of the component response model of Section 4.2 with a fixture model and a shaker facility response model. The shaker facility response model relates the shaker table acceleration response to the driving voltage input. Such a model will also allow quantification of the effects of uncontrollable shaker and fixture dynamic response on the component damage potential metrics for appropriate tailoring of the suite of SDOF tests for a specific laboratory shaker.

4.4) Areas 4.1 and 4.2 will allow test specification engineers to provide specifications with quantified margins for damage potential. Area 4.3 will allow the test facility to provide the best approximation to the intent of the SDOF qualification specifications by mitigating undesirable resonant effects inherent in the dynamics of the shaker hardware. Meeting these near-term research goals will dramatically increase qualification confidence with well quantified margin and eliminate (often unrecognized) cost and schedule waste due to currently unschooled over-testing. The potential for the less common, but potentially more disastrous case of under-testing in qualification due to the laboratory boundary condition difference is also mitigated with a well quantified margin.

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